A Comparative Technoeconomic Analysis of Renewable Generation of Methane Using Sunlight, Water and Carbon Dioxide: Supplementary Information

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Analytical basis

Relevant process assumption and cost information for direct air capture (DAC),[1] low-temperature electrolysis (LTE),[2,3] high-temperature electrolysis (HTE),[3,4] solar thermochemical hydrogen (STCH), and thermochemical methanation[5] were solicited from available reports. Various sources were adopted to develop process and cost estimates for ocean capture,[6–10] photoelectrochemical (PEC) hydrogen generation,[11,12] grid electrolysis methanation,[3,4] PEC methanation,[11,12] and biochemical methanation.[13,14] The plant design capacity was assumed to be 240 ton/day for CO_2 capture, 45 ton/day for H_2 generation, 81 ton/day for CH_4 production.

In some cases where cost information were already available in a certain plant capacity, the costs of similar items of different sizes were approximated to our specific design capacity using exponential scaling factor, as follows:

$$C_{\mathrm{D}} = C_{\mathrm{B}} \left(\frac{S_D}{S_B} \right)^N \tag{2}$$

where C_{D} is the cost at design capacity, C_{B} is the cost at known baseline capacity, S_{D} is the design capacity, S_{B} is the known baseline capacity, and N is the scaling factor exponent that varies from 0.1 to unity. Unless otherwise specified, an average value of 0.6 was as used for N.

All equipment capital costs reported in the past were adjusted to 2019 dollars by multiplying the reported base cost from an earlier year by the ratio of a cost index (I) in 2019 to a base cost index (I_{base}) that corresponds to the year of which the cost information was obtained:[10]

$$C_{2019} = C_{\mathrm{R}} \frac{I_{2019}}{I_{\mathrm{R}}} \tag{2}$$

where C_{2019} is the equipment purchase cost in 2019, C_{R} is the equipment purchase cost in reference year, I_{2019} is the Chemical Engineering Plant Cost Index (CEPCI) in 2019 and I_{R} is CEPCI in reference year.

The calculated results of the levelized product costs were adjusted to 2020 dollars using inflation rate of 1.9%:

$$LCP_{2020} = LCP_{2019} \, (1 + 1.9\%)^{2020-2019} \tag{3}$$

where LCP_{2020} and LCP_{2019} are the levelized cost of product in 2020 dollars and in 2019 dollars, respectively.

Table S1: The default H2A hydrogen production economic model and its financial values were applied to all systems studied.

Financial Parameters	Assumptions
Length of Construction Period (years)	1
Year of analysis	2020
% of Capital Spent in 1st Year of Construction	100%
Start-up Time (years)	1
Plant life (years)	40
Analysis period (years)	40
Depreciation Schedule Length (years)	20
Depreciation Type	MACRS
% Debt Financing	60%
% Equity Financing	40%
Interest rate on debt (%)	3.70%
Debt period (years)	Constant debt
% of Fixed Operating Costs During Start-up (%)	75%
% of Revenues During Start-up (%)	50%
% of Variable Operating Costs During Start-up (%)	75%
Decommissioning costs (% of depreciable capital investment)	10%
Salvage value (% of total capital investment)	10%
Inflation rate (%)	1.9%
State Taxes (%)	6.0%
Federal Taxes (%)	21.0%
Total Tax Rate (%)	25.74%
Working capital (% of yearly change in operating costs)	15%
After-tax real IRR	6%
After-tax nominal IRR	8.01%

Table S2: Assumptions for calculating the cost of direct air capture of CO_2 currently. For further information see excel sheet titled "Direct Air Capture of CO2 (current)".

Process Assumptions		
Design capacity	244444.44	kg CO_2/day
Average production	220000	kg CO_2/day
Capacity factor	0.9	
Baseline capacity	2684931.507	kg CO_2/day
Scale ratio	0.09	
Fan energy	61	kWh/t-CO_2
Fluid pumping energy	21	kWh/t-CO_2
Fluid pumping energy	27	kWh/t-CO_2
Power produced from slaking heat	-77	kWh/t-CO_2
Energy consumption	32	kWh/t-CO_2
ASU power usage	238	kWh/t-CO_2
Compressor power usage	132	kWh/t-CO_2
Calciner	369	kWh/t-CO_2
Water consumption	4.7	t-water/t-CO_2
Water price	0.69307362	$/t-water
Industrial electricity	0.049	$/kWh
Natural gas price	3.5	$/GJ

Baseline system cost				
	Baseline installed cost in startup year dollars	Installation cost factor	Combined plant scaling	Installed cost
Air contactor	$135,867,821	1.86	0.09	$22,984,912
Pellet reactor	$91,490,678	1.70	0.09	$14,167,891
Calciner-slaker	$52,110,425	1.77	0.15	$13,591,553
Air separation unit	$45,209,958	1.43	0.24	$15,339,052
CO_2 compressor	$20,463,455	1.16	0.20	$4,777,228
Steam turbine	$7,971,229	1.12	0.19	$1,667,188
Power plant	$38,904,359	1.07	0.30	$12,564,408
Fines filter	$20,939,349	1.76	0.24	$8,728,853
Other equipment	$115,285,393	1.06	0.24	$29,039,678
Buildings	$2,974,339	2.68	0.43	$3,445,575
Transformer	$22,129,085	1.06	0.33	$7,822,927
Total				**$134,129,266**

Capital costs	
Depreciable capital costs	Value in startup year dollars
Direct capital cost	$134,129,266
Indirect capital cost	
Site preparation (2% direct capital cost)	$2,682,585
Engineering and design (10% direct capital cost)	$13,412,927
Project contingency (15% direct capital cost)	$20,119,390
Upfront permitting cost (legal and contractors fees) (7.5% direct capital cost)	$10,059,695
Total capital cost	**$180,403,863**

Fixed operating costs	
	Value in startup year
Labor cost ($50/FTE) ($/year) (11 FTE)	$1,282,289
G&A ($/year) (20% labor cost)	$256,458
Property taxes and insurance ($/year) (2% total capital cost)	$3,608,077
Production maintenance and repairs ($/year) (2.9% direct capital cost)	$3,889,749
Total fixed operating costs ($/year)	$9,036,573

Variable operating costs	
	Value in startup year
Energy utilities costs	$17,823,995
Non energy utilities costs	$3,032,682
Total variable operating costs ($/year)	**$20,856,677**

Replacements	
	Value in startup year
Unplanned replacement capital cost (0.5% of total direct capital costs/year)	$670,646

Table S3: Assumptions for calculating the cost of direct air capture of CO_2 in the future. For further information see excel sheet titled "Direct Air Capture of CO2 (future)".

Process Assumptions		
Design capacity	2684931.51	kg CO_2/day
Average production	2550684.932	kg CO_2/day
Capacity factor	0.95	
Baseline capacity	2684931.507	kg CO_2/day
Scale ratio	1	
Scaling factor exponent	0.6	
Electricity equivalent gas input	478.3333333	kWh/t-CO_2
Electricity input	77	kWh/t-CO_2
Water consumption	4.7	t-water/t-CO_2
Water price	0.69307362	$/t-water
Industrial electricity	0.01	$/kWh
Natural gas price	3.5	$/GJ

Baseline system cost			
	Uninstalled cost in startup year dollars	Installation cost factor	Installed cost
Air contactor	$157,996,906	1.00	$157,996,906
Pellet reactor	$112,786,948	1.00	$112,786,948
Calciner-slaker	$75,667,193	1.00	$75,667,193
Air separation unit	$55,560,659	1.00	$55,560,659
CO_2 compressor	$18,440,904	1.00	$18,440,904
Steam turbine	$6,900,467	1.00	$6,900,467
Power plant	$31,765,944	1.00	$31,765,944
Fines filter	$29,505,446	1.00	$29,505,446
Other equipment	$91,609,652	1.00	$91,609,652
Buildings	$6,900,467	1.00	$6,900,467
Transformer	$19,868,587	1.00	$19,868,587
Total			**$607,003,173**

Capital costs	
Depreciable capital costs	Value in startup year dollars
Direct capital cost	$607,003,173
Indirect capital cost	
Site preparation (2% direct capital cost)	$12,140,063
Engineering and design (10% direct capital cost)	$60,700,317
Project contingency (15% direct capital cost)	$91,050,476
Upfront permitting cost (legal and contractors fees) (7.5% direct capital cost)	$45,525,238
Total capital cost	**$816,419,268**

Fixed operating costs	
	Value in startup year dollars
Labor cost ($50/FTE) ($/year) (46.34 FTE)	$5,402,081
G&A ($/year) (20% labor cost)	$1,080,416
Property taxes and insurance ($/year) (2% total capital cost)	$16,328,385
Production maintenance and repairs ($/year) (2.9% direct capital cost)	$17,603,092
Total fixed operating costs ($/year)	$40,413,974

Variable operating costs	
	Value in startup year dollars
Energy utilities costs	$17,823,995
Non energy utilities costs	$3,032,682
Total variable operating costs ($/year)	**$20,856,677**

Replacements	
	Value in startup year dollars
Unplanned replacement capital cost (0.5% of total direct capital costs/year)	$670,646

Table S4: Assumptions for calculating the cost of ocean CO_2 capture currently. For further information see excel sheet titled "Ocean CO2 Capture (current)".

Process Assumptions		
Design capacity	246575.34	kg CO_2/day
Average production rate	221917.8082	kg CO_2/day
Capacity factor	0.9	
Extraction efficiency	0.9	
Electrodialysis acidified stream target pH	0.40	
Oceanwater target pH	4	
Current density	100	mA/cm^2
Voltage	1.2	V
Electrodialysis energy at oceanwater target pH	0.97736927	kWh/kg CO_2
CO2 stripping energy	0.072994345	kWh/kg CO_2
Intake energy (0.5 bar, 5 m intake)	0.206827333	kWh/kg CO_2
Pre-treatment energy (3 bar ultrafiltration, 7.6 bar nanofiltration, 0.5 bar electrodialyzer)	0.04804125	kWh/kg CO_2
Pump energy (0.5 bar membrane contactor)	0.206827333	kWh/kg CO_2
Industrial electricity	0.049	$/kWh

Baseline system cost			
	Uninstalled cost in startup year dollars	Installation cost factor	Installed cost
Electrodialyzer	$15,133,812	1.20	$18,160,574
Pre-treatment	$6,657,344	1.20	$7,988,813
Gas stripping	$21,691,109	1.20	$26,029,331
Intake	$6,717,271	1.20	$8,060,725
Screening	$22,973,169	1.20	$27,567,802
Pumping	$3,747,976	1.20	$4,497,572
Total			**$92,304,818**

Capital costs	
Depreciable capital costs	Value in startup year dollars
Direct capital cost	$92,304,818
Indirect capital cost	
Site preparation (2% direct capital cost)	$1,846,096
Engineering and design (10% direct capital cost)	$9,230,482
Project contingency (15% direct capital cost)	$13,845,723
Upfront permitting cost (legal and contractors fees) (7.5% direct capital cost)	$6,922,861
Total capital cost	**$124,149,981**

Fixed operating costs	
	Value in startup year dollars
Labor cost ($50/FTE) ($/year) (34.95 FTE)	$4,074,146
G&A ($/year) (20% labor cost)	$814,829
Property taxes and insurance ($/year) (2% total capital cost)	$2,483,000
Production maintenance and repairs ($/year) (2.9% direct capital cost)	$2,769,145
Total fixed operating costs ($/year)	**$10,141,120**

Variable operating costs	
	Value in startup year
Energy utilities costs	$6,001,364
Non energy utilities costs	$0
Total variable operating costs ($/year)	**$6,001,364**

Replacements	
	Value in startup year dollars
Unplanned replacement capital cost (0.5% of total direct capital costs/year)	$461,524.09
Replacement costs (15% of depreciable capital cost/5year)	$18,622,497.08
Specified replacement cost (electrodialyzer/5year)	$18,160,574.35
Specified replacement cost (60% pre-treatment/5year)	$4,793,288.03
Specified replacement cost (gas stripping/10year)	$26,029,331.20

Table S5: Assumptions for calculating the cost of ocean CO_2 capture in the future. For further information see excel sheet titled "Ocean CO2 Capture (future)".

Process Assumptions		
Design capacity	2739726.03	kg CO_2/day
Average production rate	2602739.726	kg CO_2/day
Capacity factor	0.95	
Extraction efficiency	0.98	
Electrodialysis acidified stream target pH	0.40	
Oceanwater target pH	4	
Current density	1000	mA/cm^2
Voltage	1.6	V
Electrodialysis energy at oceanwater target pH	1.196778698	kWh/kg CO_2
CO2 stripping energy	0.072994345	kWh/kg CO_2
Intake energy (0.5 bar, 5 m intake)	0.189943469	kWh/kg CO_2
Pre-treatment energy (3 bar ultrafiltration, 7.6 bar nanofiltration, 0.5 bar electrodialyzer)	0.044119516	kWh/kg CO_2
Pump energy (0.5 bar membrane contactor)	0.189943469	kWh/kg CO_2
Industrial electricity	0.01	$/kWh

Baseline system cost			
	Uninstalled cost in startup year dollars	Installation cost factor	Installed cost
Electrodialyzer	$7,721,333	1.00	$7,721,333
Pre-treatment	$25,033,436	1.00	$25,033,436
Gas stripping	$73,347,986	1.00	$73,347,986
Intake	$68,543,583	1.00	$68,543,583
Screening	$234,420,087	1.00	$234,420,087
Pumping	$38,244,657	1.00	$38,244,657
Total			**$447,311,082**

Capital costs	
Depreciable capital costs	Value in startup year dollars
Direct capital cost	$447,311,082
Indirect capital cost	
Site preparation (2% direct capital cost)	$8,946,222
Engineering and design (10% direct capital cost)	$44,731,108
Project contingency (15% direct capital cost)	$67,096,662
Upfront permitting cost (legal and contractors fees) (7.5% direct capital cost)	$33,548,331
Total capital cost	**$601,633,406**

Fixed operating costs	
	Value in startup year dollars
Labor cost ($50/FTE) ($/year) (126.79 FTE)	$14,780,298
G&A ($/year) (20% labor cost)	$2,956,060
Property taxes and insurance ($/year) (2% total capital cost)	$12,032,668
Production maintenance and repairs ($/year) (2.9% direct capital cost)	$13,419,332
Total fixed operating costs ($/year)	**$43,188,359**

Variable operating costs	
	Value in startup year
Energy utilities costs	$16,090,905
Non energy utilities costs	$0
Total variable operating costs ($/year)	**$16,090,905**

Replacements	
	Value in startup year dollars
Unplanned replacement capital cost (0.5% of total direct capital costs/year)	$2,236,555
Replacement costs (15% of depreciable capital cost/5year)	$60,163,341
Specified replacement cost (electrodialyzer/5year)	$7,721,333
Specified replacement cost (60% pre-treatment/5year)	$25,033,436
Specified replacement cost (gas stripping/10year)	$73,347,986

Table S6: Assumptions for calculating the cost of membrane water capture. For further information see excel sheet titled "Membrane Water Capture".

Process Assumptions		
Design capacity	365000	kg H_2O/day
Average production rate	357700	kg H_2O/day
Capacity factor	98%	

System cost			
	Uninstalled cost in startup year dollars	Installation cost factor	Installed cost
Equipment cost	$52,581,424	1.00	$52,581,424
Total			**$52,581,424**

Capital costs	
	Value in startup year dollars
Depreciable capital costs	
Direct capital cost	$52,581,424
Indirect capital cost	
Site preparation (2% direct capital cost)	$761,944
Engineering and design (10% direct capital cost)	$3,809,721
Project contingency (15% direct capital cost)	$5,714,581
Upfront permitting cost (legal and contractors fees) (15% direct capital cost)	$5,714,581
Total capital cost	**$68,582,251**

Fixed operating costs	
	Value in startup year dollars
Labor cost ($50/FTE) ($/year) (3 FTE)	$362,980
G&A ($/year) (20% labor cost)	$67,339
Property taxes and insurance ($/year) (2% total capital cost)	$1,371,645
Production maintenance and repairs ($/year) (3% direct capital cost)	$1,577,443
Total fixed operating costs ($/year)	**$3,379,407**

Variable operating costs	
	Value in startup year dollars
Total variable operating costs ($/year)	**$321,067**

Replacements	
	Value in startup year dollars
Unplanned replacement capital cost (1% of total direct capital costs/year)	$525,814

Table S7: Assumptions for calculating the cost of condensation water capture. For further information see excel sheet titled "Condensation Water Capture".

Process Assumptions		
Design capacity	365000	kg H_2O/day
Average production rate	357700	kg H_2O/day
Capacity factor	98%	

System cost			
	Uninstalled cost in startup year dollars	Installation cost factor	Installed cost
OPUR structure	$19,993,088	1.00	$19,993,088
Pumps	$214,000	1.00	$214,000
Total			**$1,273,210,134**

Capital costs	
	Value in startup year dollars
Depreciable capital costs	
Direct capital cost	$327,803,864
Indirect capital cost	
Site preparation (2% direct capital cost)	$4,750,123
Engineering and design (10% direct capital cost)	$23,750,615
Project contingency (15% direct capital cost)	$35,625,923
Upfront permitting cost (legal and contractors fees) (15% direct capital cost)	$35,625,923
Total capital cost	**$427,556,448**

Fixed operating costs	
	Value in startup year dollars
Labor cost ($50/FTE) ($/year) (3 FTE)	$362,980
G&A ($/year) (20% labor cost)	$67,339
Property taxes and insurance ($/year) (2% total capital cost)	$8,551,129
Production maintenance and repairs ($/year) (3% direct capital cost)	$9,834,116
Total fixed operating costs ($/year)	**$18,815,564**

Variable operating costs	
	Value in startup year dollars
Total variable operating costs ($/year)	**$0**

Replacements	
	Value in startup year dollars
Unplanned replacement capital cost (1% of total direct capital costs/year)	$3,278,039

Table S8: Assumptions for calculating the cost of low temperature electrolysis for H_2 production. For further information see excel sheet titled "Low Temperature Electrolysis H2".

Process Assumptions		
Design capacity	40000	kg H_2/day
Current Density	2	A/cm^2
Voltage	1.9	V/cell
Baseline design capacity	50000	kg H_2/day
Degradation Rate	1.5	mV/1000 hrs
Cell/stack	150	
Stack Life	7	years
Hours per stack life	59480.4	hrs/life
Degradation Rate	89.2206	V/life
Stack oversize due to degradation	0.13	
Peak production rate	45200	kg H_2/day
Capacity factor	0.97	
Average production	43844	kg H_2/day
Total Active Area	2212	m^2
Total Active Area (with degradation)	2499	m^2
Total System Electrical Usage	55.5	kWh/kg H_2
Stack Electrical Usage	50.4	kWh/kg H_2
BoP Electrical Usage	5.1	kWh/kg H_2
Total System Input Power (Peak)	104.525	MW
Stack Input Power (peak)	94.92	MW
Process Water Flow Rate	3.78	gal/kg H_2
Total System Cost	460	$/kW
Stack System Cost	1.3	$/cm^2
Mechanical BoP	76.00	$/(kg H_2/day)
Electrical BoP	82	$/kW
Industrial electricity	0.049	$/kWh
Processed water	0.00263368	$(2016)/gal

Baseline system cost			
	Uninstalled cost in startup year dollars	Installation cost factor	Installed cost
Stack capital cost	$38,650,945	1.12	$43,289,058
Mechanical BoP	$4,086,980	1.00	$4,086,980
Electrical BoP	$9,260,237	1.12	$10,371,465
Total			**$57,747,504**

Capital costs	
Depreciable capital costs	
Direct capital cost	$57,747,504
Indirect capital cost	
Site preparation (2% direct capital cost)	$1,154,950
Engineering and design (10% direct capital cost)	$5,774,750
Project contingency (15% direct capital cost)	$8,662,126
Upfront permitting cost (legal and contractors fees) (15% direct capital cost)	$8,662,126
Non depreciable capital costs	
Cost of land (5 acre, $50,000/acre) (2016 dollars)	$245,459
Total capital cost	**$82,246,914**

Fixed operating costs	
Labor cost ($50/FTE) ($/year) (8.75 FTE)	$1,019,641
G&A ($/year) (20% labor cost)	$203,928
Property taxes and insurance ($/year) (2% total capital cost)	$1,644,938
Production maintenance and repairs ($/year) (3% direct capital cost)	$1,732,425
Total fixed operating costs ($/year)	**$4,600,932**

Variable operating costs	
Energy utilities costs	$43,520,322
Non energy utilities costs	$176,671
Total variable operating costs ($/year)	**$43,696,993**

Replacements	
Unplanned replacement capital cost (0.5% of total direct capital costs/year)	$410,007
Replacement costs (15% of depreciable capital cost/7year)	$8,662,126

Table S9: Assumptions for calculating the cost of high temperature electrolysis for H_2 production. For further information see excel sheet titled "High Temperature Electrolysis H2".

Process Assumptions		
Design capacity	40000	kg H_2/day
Capacity factor	0.8244	
Average production	32976	kg H_2/day
Total System Electrical Usage	50.9	kWh/kg H_2
Electrical usage	36.8	kWh/kg H_2
Heat usage	14.1	kWh/kg H_2
Heat usage	0.05613	mmBtu/kg H_2
Process Water Flow Rate	2.384702106	gal/kg H_2
Total System Cost	820	$/kW
Stack Cost (% of uninst. SOEC Sys Cost)	0.35	
BoP Cost (% of uninst. SOEC Sys Cost)	0.65	
Industrial natural gas	3.733674814	$/mmbtu
Industrial electricity	0.049	$/kWh
Processed water	0.00263368	$(2016)/gal

Baseline system cost			
	Uninstalled cost in startup year dollars	Installation cost factor	Installed cost
Stack capital cost	$38,650,945	1.12	$23,455,624
BoP	$4,086,980	1.12	$43,560,445
Total			**$67,016,069**

Capital costs	
	Value in startup year dollars
Depreciable capital costs	
Direct capital cost	$67,016,069
Indirect capital cost	
Site preparation (2% direct capital cost)	$1,340,321
Engineering and design (10% direct capital cost)	$6,701,607
Project contingency (15% direct capital cost)	$10,052,410
Upfront permitting cost (legal and contractors fees) (15% direct capital cost)	$10,052,410
Non depreciable capital costs	
Cost of land (1 acre, $50,000/acre) (2016 dollars)	$49,092
Total capital cost	**$95,211,910**

Fixed operating costs	
	Value in startup year dollars
Labor cost ($50/FTE) ($/year) 13.12 FTE)	$1,529,461
G&A ($/year) (20% labor cost)	$305,892
Property taxes and insurance ($/year) (2% total capital cost)	$1,904,238
Production maintenance and repairs ($/year) (3% direct capital cost)	$2,010,482
Total fixed operating costs ($/year)	**$5,750,074**

Variable operating costs	
	Value in startup year
Energy utilities costs	$25,633,493
Non energy utilities costs	$83,829
Total variable operating costs ($/year)	**$25,717,323**

Replacements	
	Value in startup year dollars
Unplanned replacement capital cost (1% of total direct capital costs/year)	$951,628
Specified replacement costs (27.3% of stack cost/year)	$6,403,385
Specified replacement costs (100% of BoP cost/15 year)	$43,560,445

Table S10: Assumptions for calculating the cost of photoelectrochemical H_2 production currently. For further information see excel sheet titled "Photoelectrochemical H2 (current)".

Process Assumptions			
Design capacity		40000	kg H_2/day
Average production rate		40000	kg H_2/day
Location	California		
PV efficiency		19.1%	
STH efficiency		10%	
Solar power		1000	W/m^2
Solar capacity factor		28.4%	
PV module		0.37	$/W
Solar capture area for stack only		1914218	m^2
Solar capture area for BoP (10% of stack)		191421.8	m^2
Total solar capture area		2105639.8	m^2
PV cells		70.67	$/$m^2$
Catalyst		8	$/$m^2$
Membrane		30	$/$m^2$
Chassis		37.74869216	$/$m^2$
Water processing		0.76	$/$m^2$
Gas processing		6.599227784	$/$m^2$
Power electronics and control system		7.908190728	$/$m^2$
Process Water Flow Rate		3.78	gal/kg H_2
Processed water		0.00263368	$(2016)/gal

Baseline system cost	Uninstalled cost in startup year dollars	Installation cost factor	Installed cost
PV capital cost	$148,805,565	1.30	$193,447,234
Stack capital cost	$159,499,461	1.12	$178,639,396
Mechanical BoP	$15,487,230	1.00	$15,487,230
Electrical BoP	$16,651,801	1.12	$18,650,017
Total			**$406,223,878**

Capital costs	Value in startup year dollars
Depreciable capital costs	
Direct capital cost	$406,223,878
Indirect capital cost	
Site preparation (2% direct capital cost)	$8,124,478
Engineering and design (10% direct capital cost)	$40,622,388
Project contingency (15% direct capital cost)	$60,933,582
Upfront permitting cost (legal and contractors fees) (15% direct capital cost)	$60,933,582
Non depreciable capital costs	
Cost of land (520 acre, $50,000/acre) (2016 dollars)	$26,015,706
Total capital cost	**$602,853,613**

Fixed operating costs	Value in startup year dollars
Labor cost ($50/FTE) ($/year) (20.67 FTE)	$2,409,559
G&A ($/year) (20% labor cost)	$481,912
Property taxes and insurance ($/year) (2% total capital cost)	$12,057,072
Production maintenance and repairs ($/year) (3% direct capital cost)	$12,186,716
Total fixed operating costs ($/year)	**$27,135,260**

Variable operating costs	Value in startup year
Energy utilities costs	$0
Non energy utilities costs	$145,348
Total variable operating costs ($/year)	**$145,348**

Replacements	Value in startup year dollars
Unplanned replacement capital cost (0.5% of total direct capital costs/year)	$2,031,119
Replacement costs (15% of depreciable capital cost/7year)	$86,525,686
Specified replacement cost (PV stack cost/20 year)	$193,447,234

Table S11: Assumptions for calculating the cost of photoelectrochemical H_2 production in the future. For further information see excel sheet titled "Photoelectrochemical H2 (future)".

Process Assumptions			
Design capacity		40000	kg H_2/day
Average production rate		40000	kg H_2/day
Location	California		
PV efficiency		19.1%	
STH efficiency		10.0%	
Solar power		1000	W/m^2
Solar capacity factor		28.40%	
PV module		0.24	$/W
Solar capture area for stack only		957109	m^2
Solar capture area for BoP (10% of stack)		95710.9	m^2
Total solar capture area		1052819.9	m^2
PV cells		70.67	$/$m^2$
Catalyst		8	$/$m^2$
Membrane		30	$/$m^2$
Chassis		37.74869216	$/$m^2$
Water processing		0.76	$/$m^2$
Gas processing		6.599227784	$/$m^2$
Power electronics and control system		7.908190728	$/$m^2$
Process Water Flow Rate		3.78	gal/kg H_2
Processed water		0.00263368	$(2016)/gal

Baseline system cost			
	Uninstalled cost in startup year dollars	Installation cost factor	Installed cost
PV capital cost	$148,805,565	1.30	$193,447,234
Stack capital cost	$159,499,461	1.12	$178,639,396
Mechanical BoP	$15,487,230	1.00	$15,487,230
Electrical BoP	$16,651,801	1.12	$18,650,017
Total			**$406,223,878**

Capital costs	
	Value in startup year dollars
Depreciable capital costs	
Direct capital cost	$406,223,878
Indirect capital cost	
Site preparation (2% direct capital cost)	$8,124,478
Engineering and design (10% direct capital cost)	$40,622,388
Project contingency (15% direct capital cost)	$60,933,582
Upfront permitting cost (legal and contractors fees) (15% direct capital cost)	$60,933,582
Non depreciable capital costs	
Cost of land (520 acre, $50,000/acre) (2016 dollars)	$26,015,706
Total capital cost	**$602,853,613**

Fixed operating costs	
	Value in startup year dollars
Labor cost ($50/FTE) ($/year) (20.67 FTE)	$2,409,559
G&A ($/year) (20% labor cost)	$481,912
Property taxes and insurance ($/year) (2% total capital cost)	$12,057,072
Production maintenance and repairs ($/year) (3% direct capital cost)	$12,186,716
Total fixed operating costs ($/year)	**$27,135,260**

Variable operating costs	
	Value in startup year
Energy utilities costs	$0
Non energy utilities costs	$145,348
Total variable operating costs ($/year)	**$145,348**

Replacements	
	Value in startup year dollars
Unplanned replacement capital cost (0.5% of total direct capital costs/year)	$2,031,119
Replacement costs (15% of depreciable capital cost/7year)	$86,525,686
Specified replacement cost (PV stack cost/20 year)	$193,447,234

Table S12: Assumptions for calculating the cost of solar thermochemical H_2. For further information see excel sheet titled "Solar Thermochemical H2".

Process Assumptions		
Plant design capacity	45000	kg H_2/day
Baseline design capacity	100000	kg H_2/day
Plant capacity factor	90.00%	
Average production rate	40500	kg H_2/day
STH efficiency	20%	
Process Water Flow Rate	2.378	gal/kg H_2
Scale ratio	0.45	
Scaling factor exponent	0.78	
Lower limit for scaling capacity	20000	kg H_2/day
Upper limit for scaling capacity	200000	kg H_2/day
Processed water price	0.00263368	$(2016)/gal

System cost	Baseline uninstalled cost in reference year dollars	Scaled uninstalled cost in reference year dollars	Scaled uninstalled cost in startup year dollars	Installation cost factor	Scaled installed cost
ZrO2	$50,604	$27,145	$32,296	1	$32,296
Compression System	$36,614,848	$19,640,973	$23,367,567	1	$23,367,567
Solar Reactors	$27,852,508	$14,940,670	$17,775,449	3.17	$56,348,173
Vacuum Pumps	$4,850,000	$2,601,642	$3,095,266	3.3	$10,214,379
Water Pumps	$97,785	$52,454	$62,406	3.3	$205,940
Turbine	$693,223	$371,860	$442,415	2.15	$951,191
Heat Exchangers	$378,081	$202,811	$241,291	3.17	$764,893
Heliostats	$193,334,841	$103,708,866	$123,386,145	1	$123,386,145
Secondary Concentrators	$738,859	$396,340	$471,539	1	$471,539
Towers	$72,990,255	$39,153,505	$46,582,324	1	$46,582,324
Ferrite	$50,999,508	$27,357,206	$32,547,846	1	$32,547,846
Total	**$388,600,513**				**$294,872,293**

Capital costs	Value in startup year dollars
Depreciable capital costs	
Direct capital cost	$294,872,293
Indirect capital cost	
Site preparation (2% direct capital cost)	$7,016,402
Engineering and design (17.8% solar subsystem cost)	$36,094,585
Project contingency (16.8% solar and 18% chemical system cost)	$60,714,276
Upfront permitting cost (legal and contractors fees) (7.5% direct capital cost)	$26,311,508
Non depreciable capital costs	
Cost of land (374.44 acre, $50,000/acre) (2016 dollars)	$1,842,960
Total capital cost	**$426,852,024**

Fixed operating costs	Value in startup year dollars
Labor cost ($50/FTE) ($/year) (239.07 FTE)	$4,554,227
G&A ($/year) (20% labor cost)	$910,845
Property taxes and insurance ($/year) (2% total capital cost)	$8,537,040
Production maintenance and repairs ($/year) (0.5% solar + 6% nonsolar)	$8,318,137
Total fixed operating costs ($/year)	**$22,320,251**

Variable operating costs	
Energy utilities costs	$0
Non energy utilities costs	$92,581
Environmental surcharges	$1,208,144
Total variable operating costs ($/year)	**$1,300,725**

Replacements	Value in startup year dollars
Unplanned replacement capital cost (0.5% of total direct capital costs/year)	$2,125,045
Specified replacement costs (ZrO_2 and Ferrite/5 year)	$32,580,141

Table S13: Assumptions for calculating the cost of biochemical methanation. For further information see excel sheet titled "Biochemical Methanation".

Process Assumptions		
Design capacity	85714	kg SNG/day
Average production	84000	kg SNG/day
Capacity factor	98%	
H_2 input rate	42857	kg/day
CO_2 input rate	235714	kg/day
H_2 price (LTE H_2)	3.50	$/kg
CO_2 price (DAC CO_2)	0.28	$/kg

System cost				
	Uninstalled cost in reference year dollars	Uninstalled cost in startup year dollars	Installation cost factor	Installed cost
Compressor	$5,299,039	$6,061,570	1.00	$6,061,570
Methanation	$15,799,014	$18,072,489	1.00	$18,072,489
Piping installation				$4,826,812
Total				**$28,960,870**

Capital costs	
	Value in startup year dollars
Depreciable capital costs	
Direct capital cost	$28,960,870
Indirect capital cost	
Site preparation (2% direct capital cost)	$506,353
Engineering and design (10% direct capital cost)	$2,531,766
Project contingency (15% direct capital cost)	$3,797,650
Upfront permitting cost (legal and contractors fees) (15% direct capital cost)	$3,797,650
Total capital cost	**$39,594,290**

Fixed operating costs	
	Value in startup year dollars
Labor cost ($50/FTE) ($/year) (12 FTE)	$1,449,927
G&A ($/year) (20% labor cost)	$268,985
Property taxes and insurance ($/year) (2% total capital cost)	$791,886
Production maintenance and repairs ($/year) (3% direct capital cost)	$868,826
Total fixed operating costs ($/year)	**$3,379,624**

Variable operating costs	
	Value in startup year dollars
Energy utilities costs	$0
H_2 cost	$53,596,721
CO_2 cost	$23,448,298
Total variable operating costs ($/year)	**$53,596,721**

Replacements	
	Value in startup year dollars
Unplanned replacement capital cost (1% of total direct capital costs/year)	$289,609

Table S14: Assumptions for calculating the cost of thermochemical methanation. For further information see excel sheet titled "Thermochemical Methanation".

Process Assumptions		
Design capacity	81100	kg SNG/day
Average production	79478	kg SNG/day
Capacity factor	98%	
H_2 input rate	40000	kg/day
CO_2 input rate	218200	kg/day
H_2 price (LTE H_2)	3.50	$/kg
CO_2 price (DAC CO_2)	0.28	$/kg

System cost				
	Uninstalled cost in reference year dollars	Uninstalled cost in startup year dollars	Installation cost factor	Installed cost
Heat exchangers	1957000	2701033.858	1	2701033.858
Reactors	2919000	4028777.635	1	4028777.635
Catalyst (Ni supported)	318000	438900.7496	1	438900.7496
Compressors	5126000	7074859.252	1	7074859.252
MDEA unit	1049000	1447820.397	2.47	3576116.381
Membrane unit	263000	362990.2426	2.47	896585.8991
Organic Rankine Cycle Unit	1100000	1518210.14	2.47	3749979.046
Pumps	$214,000	$295,361	1.00	$295,361
Cooling tower	$555,000	$766,006	1.00	$766,006
Piping installation				$4,705,524
Total				**$28,233,144**

Capital costs	
	Values in startup year dollars
Depreciable capital costs	
Direct capital cost	$28,233,144
Indirect capital cost	
Site preparation (2% direct capital cost)	$564,663
Engineering and design (10% direct capital cost)	$2,823,314
Project contingency (15% direct capital cost)	$4,234,972
Upfront permitting cost (legal and contractors fees) (15% direct capital cost)	$4,234,972
Total capital cost	**$40,091,064**

Fixed operating costs	
	Values in startup year dollars
Labor cost ($50/FTE) ($/year) (12 FTE)	$1,398,861
G&A ($/year) (20% labor cost)	$279,772
Property taxes and insurance ($/year) (2% total capital cost)	$801,821
Production maintenance and repairs ($/year) (3% direct capital cost)	$846,994
Total fixed operating costs ($/year)	**$3,327,448**

Variable operating costs	
	Values in startup year
Energy utilities costs	$0
H_2 cost	$50,023,606
CO_2 cost	$21,706,018
Total variable operating costs ($/year)	**$71,729,624**

Replacements	
	Values in startup year dollars
Unplanned replacement capital cost (1% of total direct capital costs/year)	$282,331

Table S15: Assumptions for calculating the cost of electrochemical methanation. For further information see excel sheet titled "Low Temperature electrochemical CH4".

Process Assumptions		
Design capacity	81000	kg CH_4/day
Current Density	0.5	A/cm^2
Voltage	4	V/cell
Cell/stack	150	
Degradation Rate	0.5	mV/1000 hrs
Stack Life	7	years
Degradation Rate	30.66	V/life
Stack oversize due to degradation	0.045	
Peak production rate	84645	kg CH_4/day
Capacity factor	0.97	
Average production	82105.65	kg CH_4/day
Total Active Area	10642	m^2
Total Active Area (with degradation)	11121	m^2
Total System Electrical Usage	65.61	kWh/kg CH_4
Stack Electrical Usage	63.06	kWh/kg CH_4
BoP Electrical Usage	2.55	kWh/kg CH_4
Total System Input Power (Peak)	231.41	MW
Stack Input Power (peak)	222.41	MW
Utilization	100%	
Process Water Flow Rate	1.89	gal/kg H_4
Process CO_2 Flow Rate	2.75	kg/kg H_4
Total System Cost	460	$/kW
Stack System Cost	1.3	$/$cm^2$
Mechanical BoP	38.00	$/(kg CH_4/day)
Electrical BoP	82	$/kW
Industrial electricity	0.049	$/kWh
Processed water	0.00263368	$(2016)/gal
CO_2 (DAC)	0.28	$/kg CH_4

System cost			
	Uninstalled cost in startup year dollars	Installation cost factor	Installed cost
Stack capital cost	$172,003,665	1.12	$192,644,104
Mechanical BoP	$3,826,797	1.00	$3,826,797
Electrical BoP	$21,698,172	1.12	$24,301,952
Total			**$220,772,854**

Capital costs	
Depreciable capital costs	
Direct capital cost	$220,772,854
Indirect capital cost	
Site preparation (2% direct capital cost)	$4,415,457
Engineering and design (10% direct capital cost)	$22,077,285
Project contingency (15% direct capital cost)	$33,115,928
Upfront permitting cost (legal and contractors fees) (15% direct capital cost)	$33,115,928
Non depreciable capital costs	$313,497,452
Cost of land (4.4 acre, $50,000/acre) (2016 dollars)	$247,296
Total capital cost	**$313,744,748**

Fixed operating costs	
Labor cost ($50/FTE) ($/year) (8.81 FTE)	$1,027,269
G&A ($/year) (20% labor cost)	$205,454
Property taxes and insurance ($/year) (2% total capital cost)	$6,274,895
Production maintenance and repairs ($/year) (3% direct capital cost)	$6,623,186
Total fixed operating costs ($/year)	**$14,130,803**

Variable operating costs	
Energy utilities costs	$96,348,776
CO_2 cost	$22,919,497
H_2O cost	$165,424
Total variable operating costs ($/year)	**$119,433,698**

Replacements	
Unplanned replacement capital cost (0.5% of total direct capital costs/year)	$1,567,487
Replacement costs (15% of depreciable capital cost/7year + unplanned cost)	$33,115,928

Table S16: Assumptions for calculating the cost of photoelectrochemical methanation. For further information see excel sheet titled "Photoelectrochemical CH4".

Process Assumptions			
Design capacity		81000	kg CH_4/day
Average production rate		81000	kg CH_4/day
Location	California		
PV efficiency		19.1%	
STH efficiency		6.0%	
Solar power		1000	W/m^2
Solar capacity factor		28.40%	
PV module		0.37	$/W
Solar capture area for stack only		6460484	m^2
Solar capture area for BoP (10% of stack)		646048.4	m^2
Total solar capture area		7106532.4	m^2
PV cells		70.67	$/$m^2$
Catalyst		8	$/$m^2$
Membrane		30	$/$m^2$
Chassis		37.75	$/$m^2$
Water processing		0.23	$/$m^2$
Gas processing		1.71	$/$m^2$
Power electronics and control system		0.46	$/$m^2$
Utilization		100%	
Process CO_2 Flow Rate		2.75	kg CO_2/kg CH_4
Process Water Flow Rate		3.78	gal/kg CH_4
Processed water		0.00263368	$(2016)/gal
CO_2 (DAC)		0.28	$(2016)/gal

System cost			
	Uninstalled cost in startup year dollars	Installation cost factor	Installed cost
PV capital cost	$502,218,645	1.30	$652,884,238
Stack capital cost	$538,310,535	1.12	$602,907,799
Mechanical BoP	$13,790,861	1.00	$13,790,861
Electrical BoP	$3,238,603	1.12	$3,627,235
Total			**$1,273,210,134**

Capital costs	
Depreciable capital costs	
Direct capital cost	$1,273,210,134
Indirect capital cost	
Site preparation (2% direct capital cost)	$25,464,203
Engineering and design (10% direct capital cost)	$127,321,013
Project contingency (15% direct capital cost)	$190,981,520
Upfront permitting cost (legal and contractors fees) (15% direct capital cost)	$190,981,520
Non depreciable capital costs	
Cost of land (520 acre, $50,000/acre) (2016 dollars)	$87,802,984
Total capital cost	**$1,895,761,374**

Fixed operating costs	
Labor cost ($50/FTE) ($/year) (20.67 FTE)	$12,803,772
G&A ($/year) (20% labor cost)	$2,560,754
Property taxes and insurance ($/year) (2% total capital cost)	$37,915,227
Production maintenance and repairs ($/year) (3% direct capital cost)	$38,196,304
Total fixed operating costs ($/year)	**$91,476,057**

Variable operating costs	
Energy utilities costs	$0
CO_2 cost	$22,610,859
H_2O cost	$147,164
Total variable operating costs ($/year)	**$22,758,023**

Replacements	
Unplanned replacement capital cost (0.5% of total direct capital costs/year)	$6,366,051
Replacement costs (15% of depreciable capital cost/7year)	$271,193,758
Specified replacement cost (PV stack cost/20 year)	$652,884,238

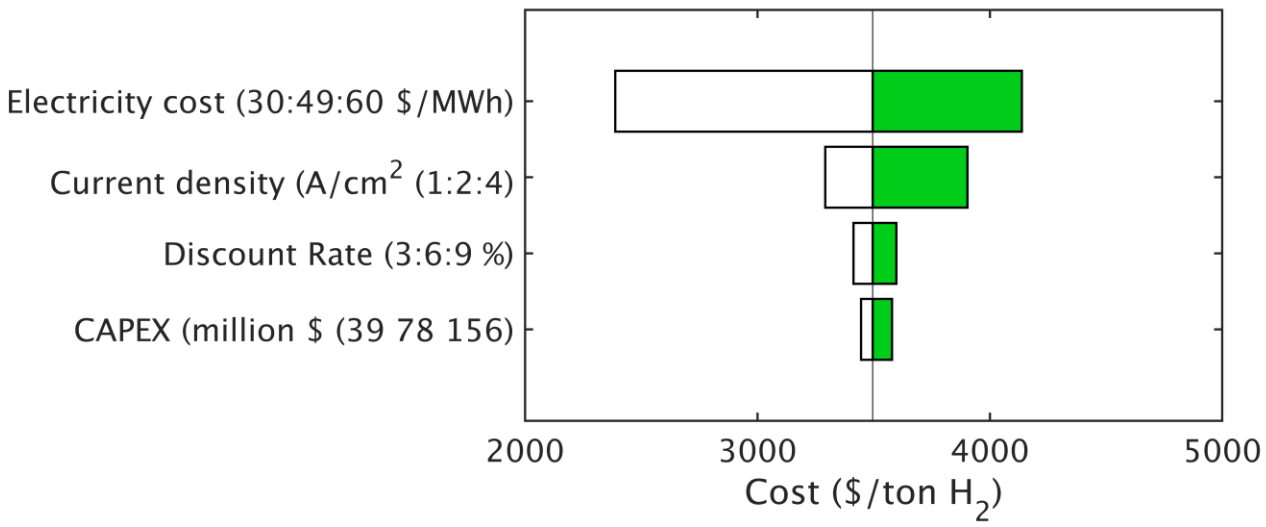

Figure S1: *Sensitivity analysis of low temperature electrolysis processes.*

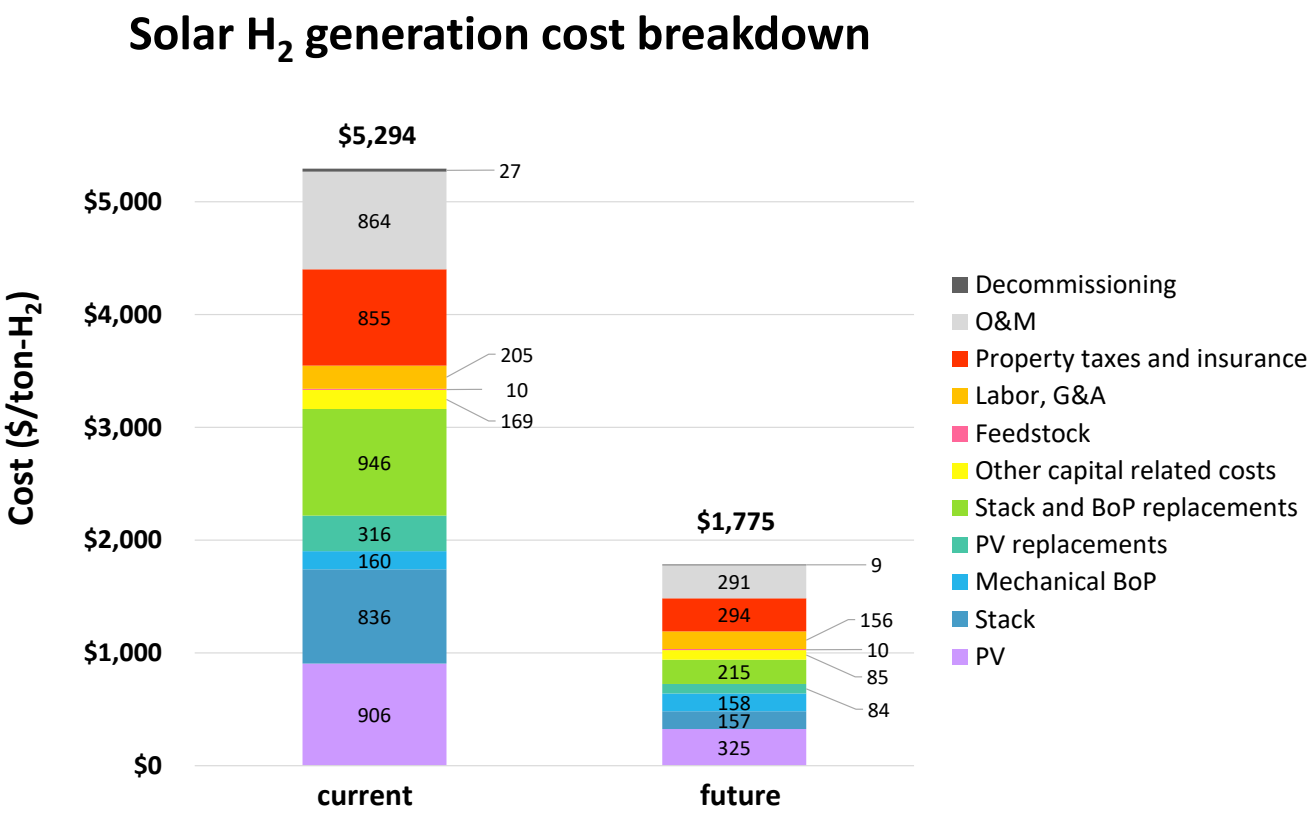

Figure S2: *Cost breakdown for current and future cost of photoelectrochemical water splitting.*

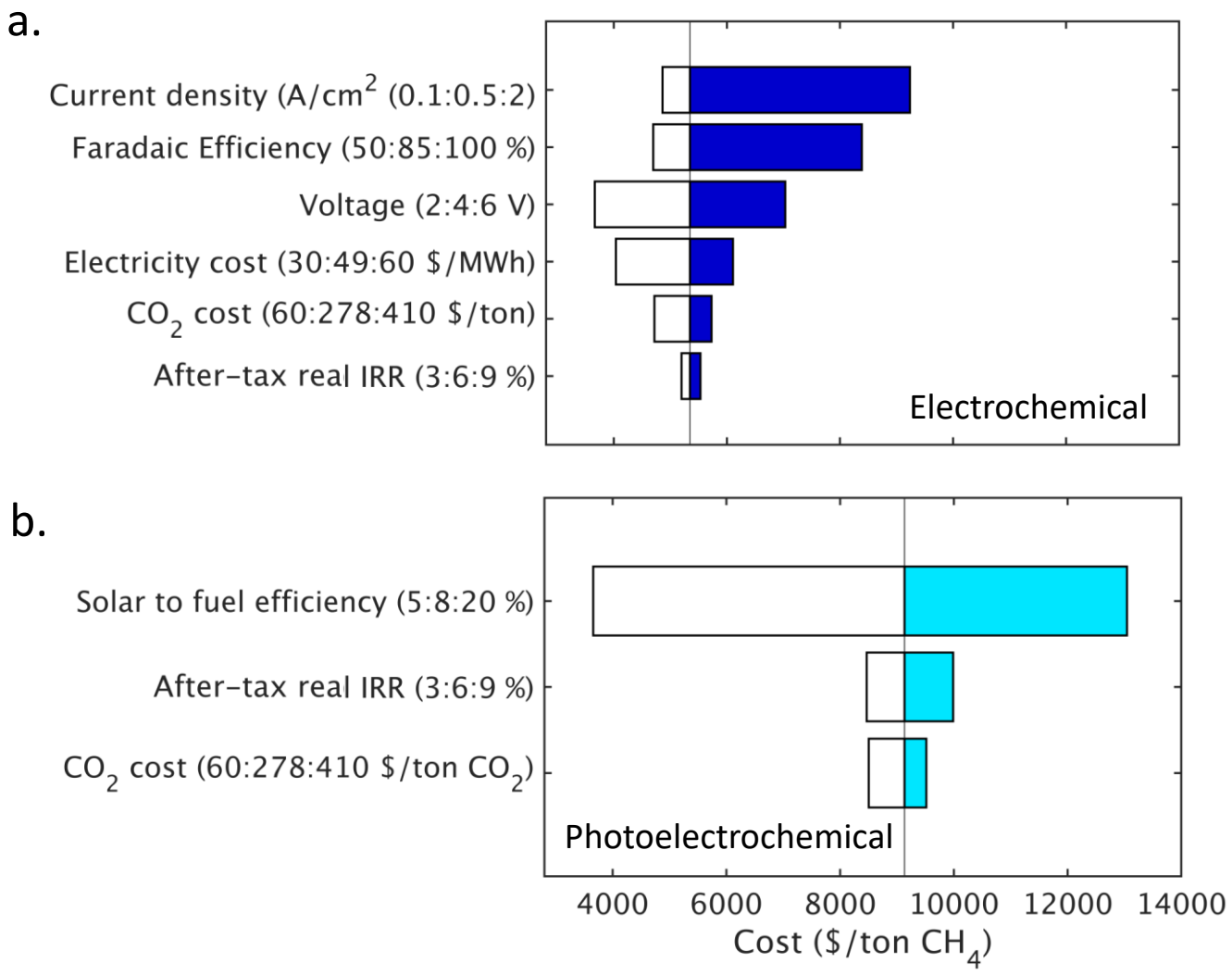

Figure S3: *Sensitivity analysis of (a) electrochemical and (b) photoelectrochemical methanation processes. The base case for the methanation processes assumes CO_2 captured from the atmosphere and H_2 generated via low temperature electrolysis.*

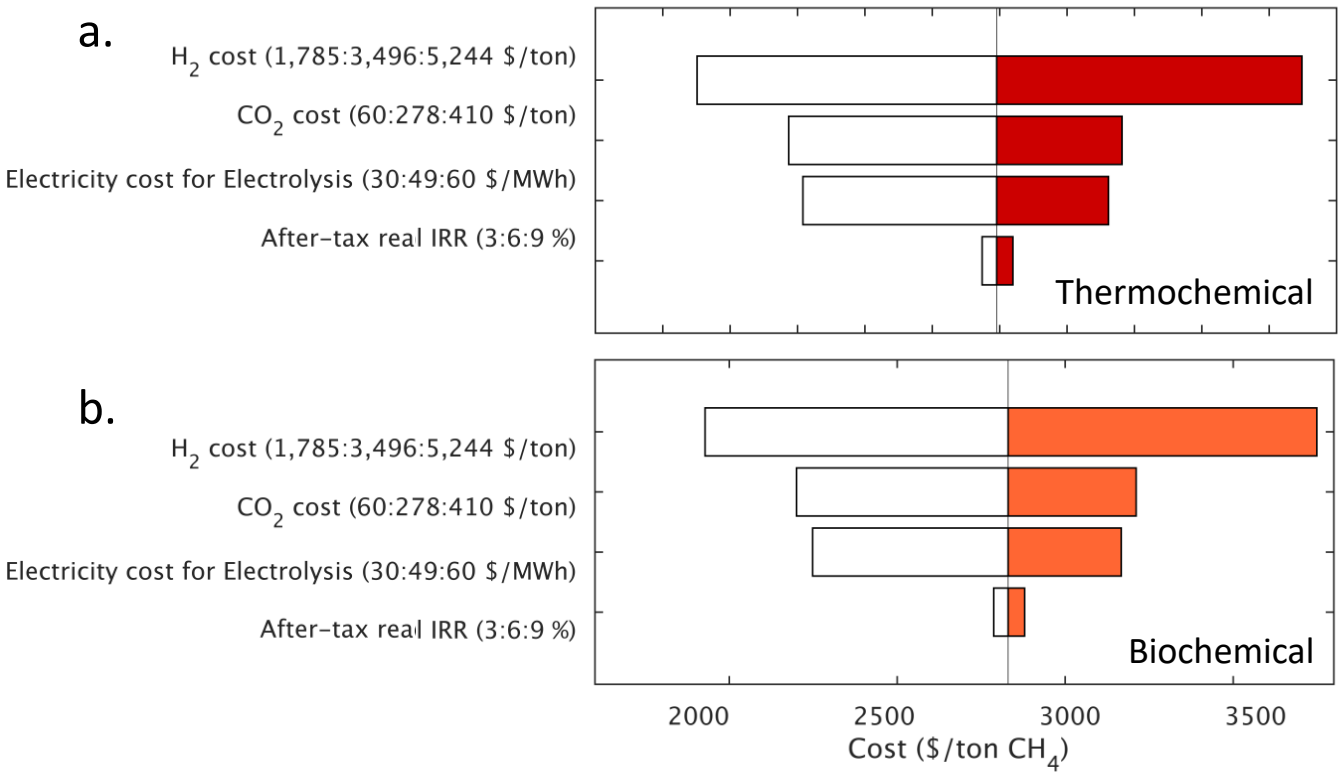

Figure S4: *Sensitivity analysis of (a) thermochemical and (b) biochemical methanation processes. The base case for the methanation processes assumes CO_2 captured from the atmosphere and H_2 generated via low temperature electrolysis.*

References:

1. Keith, D. W., Angelo, D. St., Holmes, G. & Heidel, K. A process for capturing CO_2 from the atmosphere. *Joule* **2**, 1573–1594 (2018).
2. James, B. D., Colella, W. G. & Moton, J. M. *Techno-Economic Analysis of Hydrogen Production Pathways*. *Stategic Analysis* (2013).
3. NREL. *H2A: Hydrogen Analysis Production Models*. (2018).
4. Peterson, D. & Miller, E. *Hydrogen and Fuel Cells Program Record - Hydrogen Production Cost from Solid Oxide Electrolysis*. *Hydrogen and Fuel Cells Program Record - Hydrogen Production Cost from Solid Oxide Electrolysis* (2016).
5. Becker, W. L., Penev, M. & Braun, R. J. Production of synthetic natural gas from carbon dioxide and renewably generated hydrogen: A techno-economic analysis of a power-to-gas strategy. *J. Energy Resour. Technol.* **141**, (2019).
6. de Lannoy, C. F. *et al.* Indirect ocean capture of atmospheric CO_2: Part I. Prototype of a negative emissions technology. *Int. J. Greenh. Gas Control* **70**, 243–253 (2018).
7. Eisaman, M. D. *et al.* Indirect ocean capture of atmospheric CO2: Part II. Understanding the cost of negative emissions. *Int. J. Greenh. Gas Control* **70**, 254–261 (2018).
8. Matsumiya, N., Teramoto, M., Kitada, S. & Matsuyama, H. Evaluation of energy consumption for separation of CO2 in flue gas by hollow fiber facilitated transport membrane module with permeation of amine solution. *Sep. Purif. Technol.* **46**, 26–32 (2005).
9. Voutchkov, N. *Desaliniation Engineering Planning and Design*. (McGraw-Hill Companies, Inc, 2013).
10. Seider, W. D., Seader, J. D., Lewin, D. R. & Widagdo, S. *Product and Process Design*. (John Wiley & Sons, 2009).
11. Shaner, M. R., Atwater, H. A., Lewis, N. S. & McFarland, E. W. A comparative technoeconomic analysis of renewable hydrogen production using solar energy. *Energy Environ. Sci.* **9**, 2354–2371 (2016).
12. James, B. D., Baum, G. N., Perez, J. & Baum, K. N. *Discovery of viable methanotrophic bacteria in permafrost sediments of northeast Siberia.* (2009).
13. Electrochaea. *Power-to-Gas via Biological Catalysis (P2G-Biocat)*. (2017).
14. Electrochaea. *Applications of Electrochaea's BioCat biomethanation technology*. (2018).